PFAS substitutes

A patent literature based analysis

October 2023

Dr. Jelle Demeulemeester

Mynd-Ware

TABLE OF CONTENTS

Executive Summary

Poly- and perfluoroalkyl compounds (PFAS), have found widespread applications due to their unique properties, such as chemical and thermal stability, hydrophobicity, and oleo/lipophobicity. These qualities have enabled their use in numerous industries, but they also raised environmental and health concerns. To address these concerns, the EU and global regulatory bodies have enhanced regulations. Notable actions include restrictions on PFOS and PFOA compounds within the EU REACH and POPs regulations, and the Stockholm Convention. Recent additions to regulations include PFHxS and related compounds, with ongoing considerations for long-chain PFCA compounds.

This report offers a concise overview of the innovation landscape regarding PFAS substitutes by analyzing published patents. It sheds light on trends in geographic disparities, company activity, proposed alternatives and application areas.

Four key observations are highlighted:

- **China's dominance and accelerated growth**: China leads the world in patent activity, boasting both the highest number of patents and an exceptional growth rate in its patent portfolio. European countries, apart from Germany, are notably absent from the top 10 list of country activity.
- **Diverse innovation ecosystem**: The analysis reveals active participation from both upstream and downstream producers across various industries. However, on the academic side, Chinese universities dominate patent filings, while Western universities contribute to a much smaller extend to the patent landscape of PFAS substitutes.
- **Focus on fibrous substrates**: Contemporary innovation predominantly centers around fibrous substrates, including fabrics, filters, and paper. Emerging applications gaining traction include food packaging, photovoltaic modules (PV modules), and batteries. In contrast, several sectors exhibit notably lower levels of innovation, such as cosmetics, semiconductor manufacturing, and dielectric insulators.
- **Diverse exploration of substitutes**: The report reveals a diverse exploration of substitute materials, spanning a wide spectrum of technology readiness levels, from emerging to mainstream. This diversity signifies an ongoing dynamism in the search for innovative solutions. Some of these substitute materials exhibit versatility across various applications, while others are closely associated with specific fields, indicating a multi-faceted approach to addressing industry challenges.

1. Introduction

Polyfluoroalkyl and perfluoroalkyl compounds, collectively known as PFAS, represent a class of synthetic chemicals that have garnered considerable attention in the field of chemistry, industry, and environmental science. PFAS are characterized by carbon-fluorine bonds, which belong to the strongest covalent bonds in organic chemistry. This chemical arrangement imparts several distinctive properties to PFAs, which are harnessed for a wide range of industrial and consumer applications. However, due to their persistent properties, some of these compounds also present substantial concerns for human health and the environment.

Key Properties:

- **Chemical and thermal stability**: The strong carbon-fluorine bonds and their structure render these compounds highly resistant to chemical, thermal, and biological degradation. This chemical inertness, even at elevated temperatures makes them excellent candidates for a wide variety of applications as fire resistant coatings, thermal insulation, semiconductor manufacturing, oil and gas industry, etc.
- **Hydrophobicity**: PFAS are highly hydrophobic, meaning they repel water and other polar solvents. This property is exploited in the manufacture of water-repellent coatings (especially for fabrics) and materials, as well as in firefighting foams, where it aids in extinguishing liquid fuel fires.
- **Oleo/lipophobicity**: PFAS compounds are excellent oil and fat repellents. As such, PFAS compounds pose an attractive solution in applications as food packaging, stain resistant fabrics, non-stick coatings, air filtration, automotive and mechanical components, etc.

While PFAS have found widespread utility in various industries, some compounds (depending on their properties) pose significant risks to both human health and the environment. The chemical stability that makes PFAS useful, also makes them persistent in the environment or human body. Some PFAS are associated with adverse health effects, including potential links to cancer, thyroid disease, and developmental issues. They are increasingly detected as environmental pollutants in groundwater, surface water and soil. Hence, if releases continue they will continue to accumulate in the food chain, leading to increased human exposure through food and drinking water.

In this perspective, EU and global efforts continue to strengthen the regulation for PFAS. Since 2006, perfluorooctane sulfonic acid (PFOS) related compounds have been restricted by the 2006/122/EC directive of the European Parliament and Council[1], which was eventually transferred to the REACH regulation 1907/2006[2]. By 2009, these PFOS compounds were included in the Stockholm Convention to eliminate their use. Current active regulations for PFOS, result from a revision in 2019 and can be found under the EU's Persistent Organic Pollutants (POPs) regulation 2019/1021.[3]

PFOA-related compounds were included in restriction 68 in the REACH regulation 1907/2006 since 2017, and were incorporated in the Stockholm Convention in 2019. The current EU restrictions for PFOA can be found in the POPs regulation 2019/1021, active since April 2020.
The POPs regulation was further expanded with PFHxS and related compounds in August 2023. Currently, long-chain (C9-21) PFCA's are being considered for regulation in the Stockholm Convention.

---

[1] EUR-Lex - 32006L0122 - EN - EUR-Lex (europa.eu)

[2] https://osha.europa.eu/en/legislation/directives/regulation-ec-no-1907-2006-of-the-european-parliament-and-of-the-council

[3] EUR-Lex - 32019R1021 - EN - EUR-Lex (europa.eu)

In 2019, 2020 and 2023 a number PFAS were identified and added on the REACH Candidate List of Substances of Very High Concern (SVHC): i.e. 2,3,3,3-tetrafluoro-2-(heptafluoropropoxy)propionic acid, perfluorobutane sulfonic acid (PFBS) and perfluoroheptanoic acid (PFHpA), their salts and halides. Hence, besides the general and widespread accepted health and environmental concerns, EU is continuing to shape a legal framework to further restrict and ban these substances.

This report aims to draft a high level overview of the innovation landscape of PFAS substituents, through the analysis of published patents in this field. The analysis is carried out on both meta data and the textual content of the patents. This allows to provide insights in trends related to company activity, geographical differences, proposed alternatives and their field of application.

2. Methods

About the data

Derwent innovation was used as a data source and search engine for this report. The database covers 76 jurisdictions, and augments the data with name harmonization on different levels, field indexing and "DWPI text fields". The latter feature means that a large fraction of patents have their title, abstract and claims rewritten in a "more human" non-patent language, which increases the searchability based on keywords and readability. Besides their own in-built analytics tools for the metadata, the records can be exported for further analysis with other tools.

About the analysis

The analysis was conducted in the SaaS platform Mynd[4]. Mynd is in an unsupervised topic modeling engine. Its purpose is to automatically determine a hierarchic classification of the topics that are being discussed in large textual datasets as e.g. patents or academic papers. This methods aids to give professionals both a broad and deep understanding in the context of published developments. The unsupervised approach implies that the model identifies a wide range of topics, from applications, to materials, properties and functionalities or technologies. Hence, it empowers the researcher with the capability to discover and map those concepts of interest in a very complete way, without having to read thousands of documents or requiring extensive prior knowledge. Moreover, this topical analysis is extended with innovation minded indicators, such as the "recency" and the correlation metric. The recency indicator compares the shape of the activity curve and growth rates with the overall shape and rate of the entire dataset. It allows to quantify hot trends, as well as declining and emerging trends. The recency metric will be used throughout various analysis in this report to provide insights in the recent dynamics.

[4] Confirm the known. Discover the unknown - Mynd (mynd-ware.com)

3. Search strategy and datasets

A first search exercise indicated that there are very few patents specifically indicating or describing the replacement or substitution of a PFAS compound with a non- or at least less toxic/hazardous compound. Moreover, the preferred terminology to refer to non-hazardous replacements seemed to be: "non fluorinated" or "fluorine free" and alternative writings thereof. To conduct this preliminary search, the 'Reconciling Terminology of the Universe of Per- and Polyfluoroalkyl Substances: Recommendations and Practical Guidance',[5] published by the OECD was consulted to cover the rich terminology and abbreviations marking the PFAS terminology space.

Based on these insights, a final strategy was adopted to identify patents describing a non-fluorinated alternative for at least one of the key properties of PFAS compounds. To this end, 3 different pools/queries were defined and later on combined for the analysis. The queries were constructed as follows:

- **Water repellants**: a synonym of the water repellency property (e.g. hydrophobic, waterproof, water resistant, watertight, etc.) needs to be mentioned in combination with an indication that the component is non-fluorinated. The latter part of the query requires the mentioning of an alternative writing of 'non-fluor*" OR the mentioning of the replacement of a specific PFAS compound (i.e. a synonym of free, without, … in proximity of one of the PFAS synonyms from the terminology list). This search was performed in title, abstract and claims (TAC) of the original patents, as well as in the TAC of the DWPI records. This search resulted in **2709 patent families**.
- **Oil repellants**: This query was performed in a similar way as the one for water repellents. Here, the part of the query describing the water repellent property was replaced by a query describing the oil repellent property. The oil repellent part was described with synonyms as lipophob*, oleophob, non-stick, or grease, oil, lipid or fat resistance, barrier, blocking, etc. This search was performed in title, abstract and claims (TAC) of the original patents, as well as in the TAC of the DWPI records. This search resulted in **1093 patent families**.
- **Thermal and chemical stability**: The query of this key property required the mentioning of a synonym (e.g. thermal, elevated temperature, heat, chemical, etc.) in the proximity of a synonym for stability (e.g. resist*, stabl*, robust, durab*, etc.). The part of the query describing the non-fluorinated part remained the same as for both previous queries. This search was performed in title, abstract and claims (TAC) of the original patents, as well as in the TAC of the DWPI records. This search resulted in **763 patent families**.

Combining those 3 searches results in a consolidated dataset of **3555 patent families**, which is considerably less than the sum of the separate searches – **4565 patent families**. Hence it can be concluded that none of the 3 queries are exclusive and quite some overlap is present. Indeed, many of the patents mentioning the water repellency also mention the oil repellent property.

A final check on the quality of the dataset was conducted by a manual reading of 50 patent families. In that exercise, each patent was labeled as noise or signal. In the case of noise it was determined whether this could've been avoided or not. In conclusion, based on this sample the noise ratio was

[5] Reconciling Terminology of the Universe of Per- and Polyfluoroalkyl Substances: Recommendations and Practical Guidance (oecd.org)

determined to be less than 5% which is an excellent benchmark. However, it is worth mentioning that some patents were both mentioning fluorinated as non-fluorinated alternatives.

4. Overall analysis of the patent metadata

Patent activity

The patent publication activity as a function of year is displayed in figure 1. The initial patents on this topic were published in the fifties, whereas the total publication activity sums up to 3555 patent families. 2882 Families were published in the last 20 years and have the potential to be legally active. This 20 year period is indicated in the graph by the bold black lines.

A moderate growth of patent activity is noticeable since the 90's, however, resulting in a publication dip around the year 2010. From 2011 onwards a significantly higher growth rate is observed in the data, with a well pronounced jump in publication activity in 2020. This jump in publication activity coincides with the initiation of increasing concerns of the EU. On the other hand, a possible causal relation is hard to establish from this data. From 2021 onwards one might consider a stagnation of the growth at around 300 new families a year. However, do take into account that the publication volumes of the last 18 months (i.e. 2022 and 2023) are not yet complete.

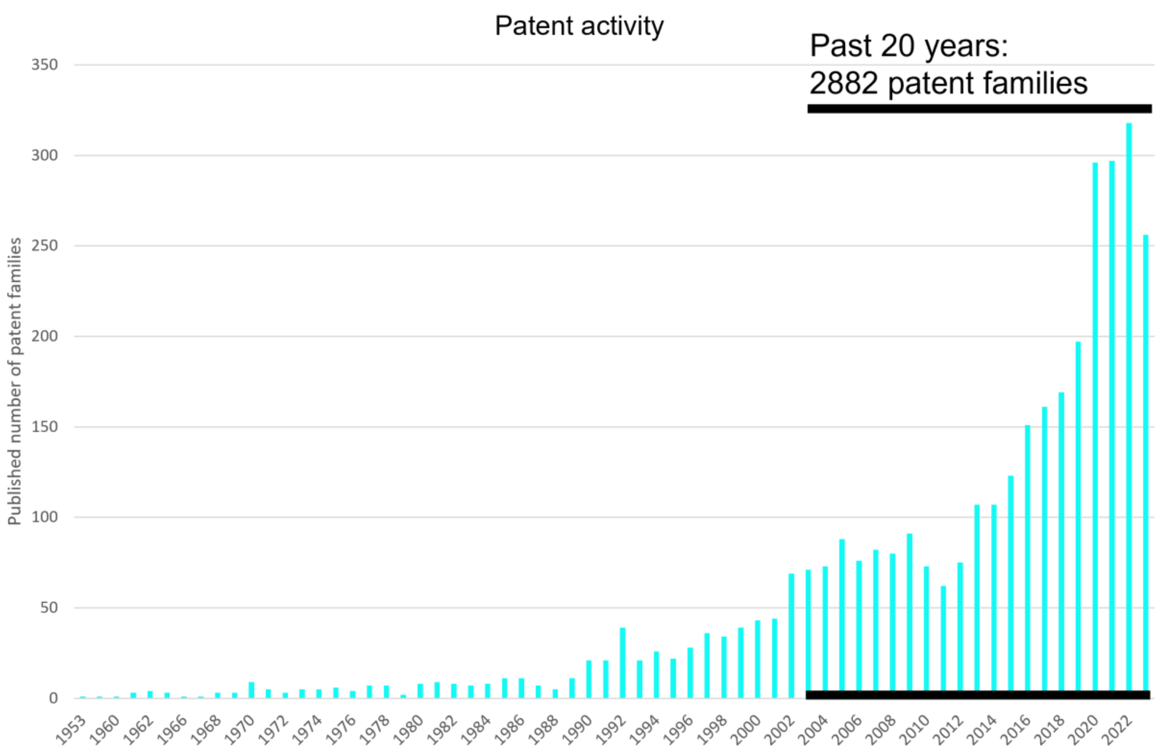

Figure 1: Publication activity of patent families as a function of year. The bold black line indicates the publication activity in the last 20 years.

Country analysis

Figure 2 displays the country code analysis. The analysis was conducted on an extension of the pool with family members as to provide a complete overview of where organizations see market potential, and thus protection is justified. Publication volumes for each country are represented by the bar length (x-axis), whereas the color code – from grey to orange – is a measure for the 'recency' metric. Orange indicates a very high growth rate (compared to the average), whereas grey indicates a significant sub average growth. EP and WO patents were discarded from the equation.

China not only holds the most patents, it also represents the fastest growing country with respect to patents in the field of PFAS alternatives. The top 3 includes Japan and the USA, and is further expanded with South Korea and Taiwan in the top 5. Germany is the only European country in the top 10. India, Taiwan and South Korea further extend the list of countries with a strong recent growth in patent activity in this field.

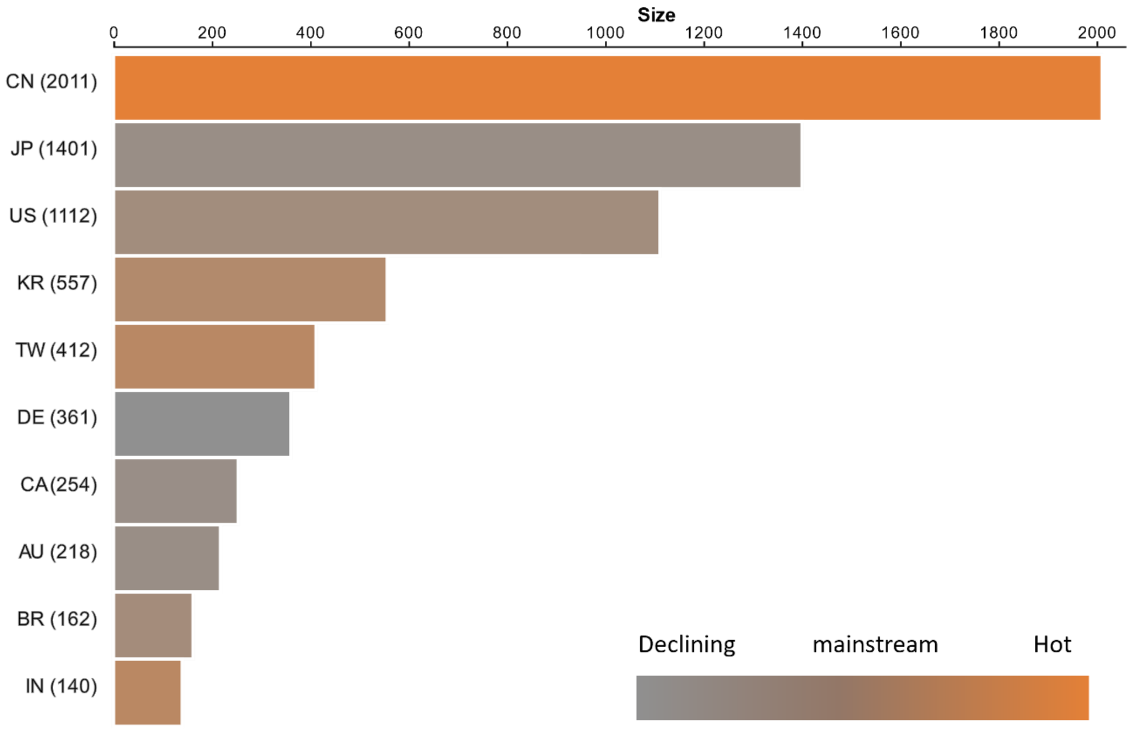

Figure 2: Country code analysis depicting the publication activity per country. This analysis was performed on a dataset including the extension with family members to provide a complete overview of where organizations are seeking protection.

Player analysis

An overview of key corporate players in this field can be found in figure 3. Daikin and AGC are – by far – filing the largest amount of patents in this field. Moreover, the recency metric shows that their rate of publication is higher than average in the most recent years. This indicates that they are actively working on the construction of a strong patent portfolio.

Furthermore, one can distinguish both upstream producers and producers that are further downstream in this top 10.

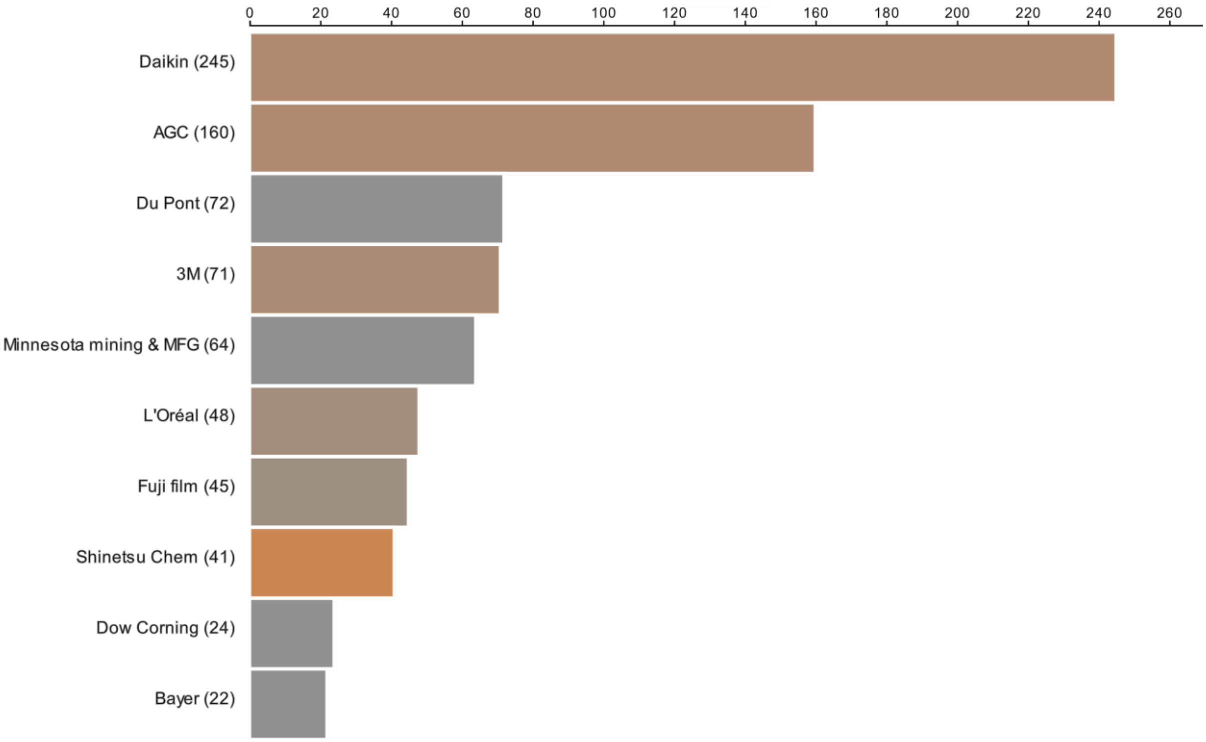

Figure 3: overview of the top 10 patent filing companies in the field of PFAS alternatives. The x-axis represents the publication volume (number of patent families), whereas the color gradient (grey to orange) is in an indicator for 'recency'

An overview of the top 10 patent filing academic players in this field can be found in figure 4. As can be observed, this list is entirely populated by Chinese universities. As a matter of fact, it is a long scroll down the entire list to encounter a first western university. Comparing the recency color codes with those of the company analysis (Figure 3) shows us that the top universities have a very recent footprint on the patent landscape of non-fluorinated PFAS alternatives. All top 10 universities have a very recent portfolio, except for Shaanxi University of Science and Technology and Shandong University in Jinan.

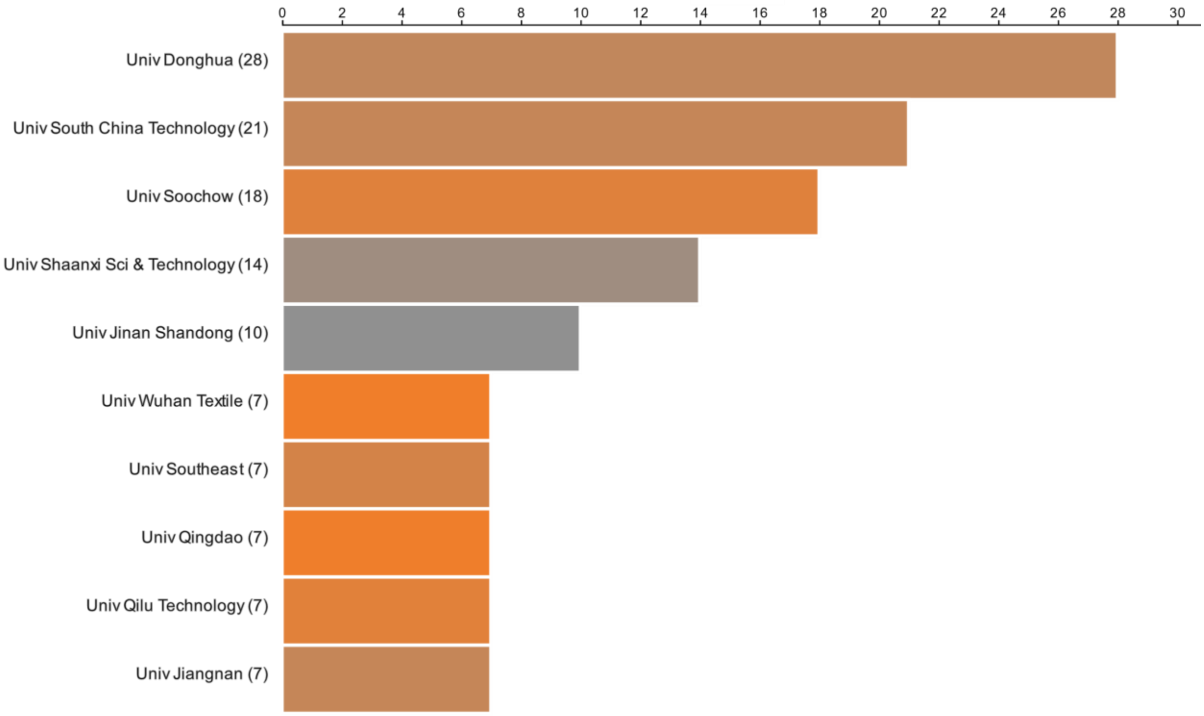

Figure 4: overview of the top 10 patent filing academic players in the field of PFAS alternatives. The x-axis represents the publication volume (number of patent families), whereas the recency is in an indicator for 'recency'

CPC classification analysis

The top 10 CPC codes at main group level are displayed in figure 5. The definitions of the CPC codes were slightly adjusted or truncated as to enhance the readability of the classification description.

As evidenced from this analysis, the top 10 is almost entirely dominated by the subclass D06M – 8 out of 10 top codes belong to this subclass. D06M is dedicated to the treatment of fibers, threads, yarns, fabrics, feathers or fibrous goods made from such materials. Most of the innovation efforts went into D06M200/12, which categorizes treatments to impart a hydrophobic property to textile.

Other, smaller, but more recent classifications are related to cellulosic fibers, polyesters, treating fibers with macromolecular compounds containing silicon in the main chain and polyurethanes or other polymers having ureide or urethane links.

DO6M15/277 is number 2 in size, but definitely in decline as indicated by the grey recency code. This main group is dedicated to patents including fluorine containing compounds. Although some patents in this group could be classified as noise, most of those patents have this code because they mention fluorine containing compounds in combination with, or alongside non-fluorinated compounds.

Analyzing the top 10 of the fastest growing classifications (i.e. high recency value) yields a different image (see figure 6). This top 10 is mainly composed out of 4 fast growing subclasses.

- D06N is related to the covering of fibrous webs with macromolecular materials, such as resins, rubbers or derivatives to produce e.g. artificial leather or oilcloths
- D21H categorizes patents in the field of paper making and pulp compositions or preparations for e.g. packaging

- C09D is dedicated to coating compositions and processes for incorporating ingredients such as inorganic, macromolecular materials or modified treatments
- B32B contains inventions describing layered products that are characterized by e.g. synthetic resins as polyester or interposed adhesives

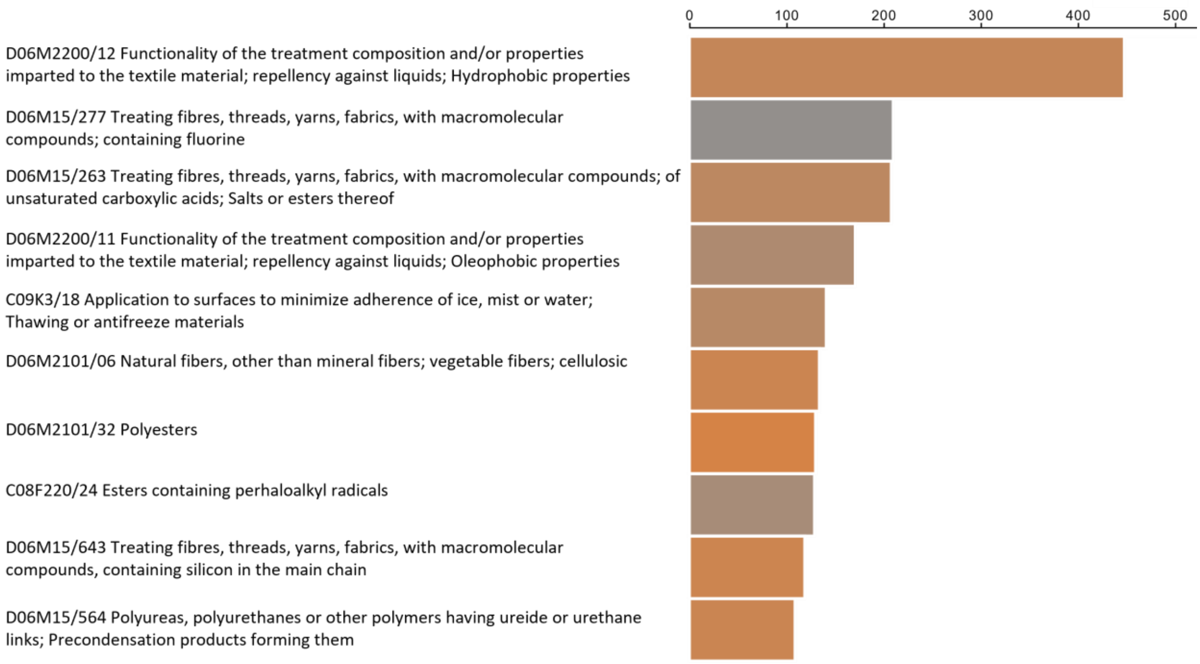

Figure 5: Overview of the top 10 assigned CPC codes at the main group level, along with their size (x-axis) and recency (grey to orange). The titles of the CPC main groups were slightly truncated or adjusted as to enhance the readability of the CPC classification

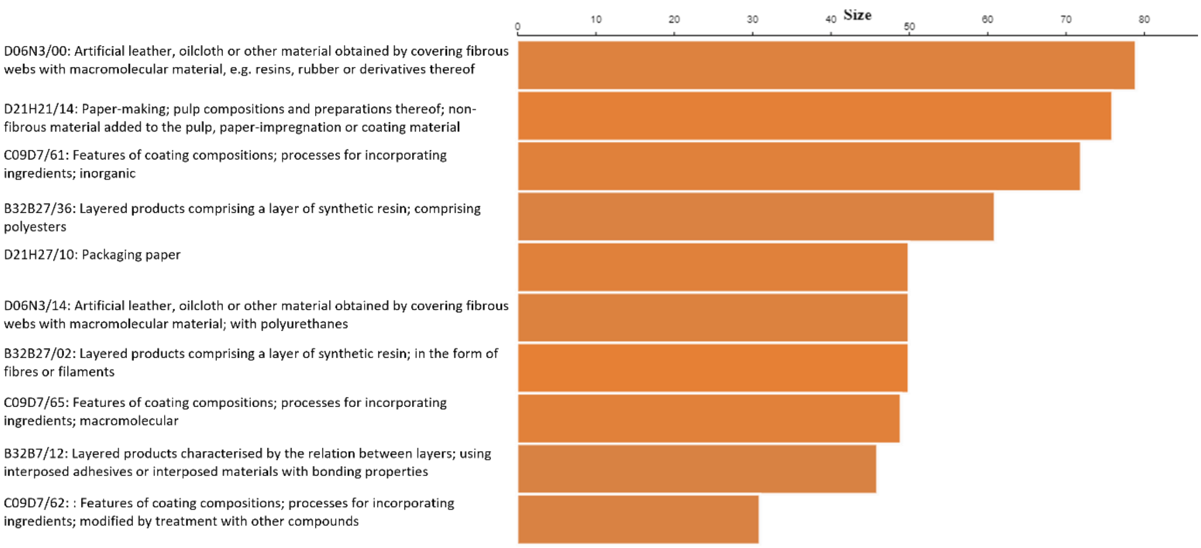

Figure 6: Overview of the top 10 assigned CPC codes at the main group level with a ***high recency*** *score. The titles of the CPC main groups were slightly truncated or adjusted as to enhance the readability of the CPC classification*

5. Overall analysis of the topic model

Field map

Mynd generates a field map based on the content and contextual relations within the titles and abstracts of the patents (see figure 7). In essences the algorithm screens for coherent topics and displays them in a map along with a title describing the field, their volume (number of families) and recency score.

The circle size is a measure for the fields volume, whereas the inclination angle and matching color of the arrow both indicate the recency value. Upward pointing arrows will have a color gradient from black to red, indicating a high recency score (i.e. trending fields). Downward facing arrows have a color gradient ranging from black over blue to purple, indicating lower recency scores (i.e. declining fields). Fields with a horizontal arrow (black) are fields that follow the general growth curve of the entire dataset.

The x- and y-axis don't have any specific meaning in this plot. However, the distance between fields (circles) is of importance. The more contextual overlap between fields (i.e. the more concepts or terminology they have in common) the closer they will be positioned. In other words, fields that have a lot in common will be placed together, forming a cluster that can be interpreted.

Since the topic modeling is unsupervised, the fields will cover a variety of aspects, ranging from materials to applications, treatments/processes, technologies, properties, etc.

Due to the richness in content in such a field map an individual interpretation exercise is definitely recommended. None the less, some guidelines for interpretation can be given:

On the left-hand side of the plot there are a considerable number of hot fields. These fields are, to a large extend, related to the waterproofing of fabrics (nonwoven and woven), or plant-based materials as paper, pulps, bamboo, etc. These fibrous material related fields on the left gradually evolve into more industrial related fields on the right-hand side. In the middle, one can notice a few hot fields like photovoltaic modules and food containers. The more we move to the right-hand side the more declining fields can be detected. This area hosts fields related to e.g. concrete fillers, insulating layers, lithography (semiconductor manufacturing), cosmetics, soil repellent finishes and rubbers. A few trending applications can be noted as well: i.e. transmission belts and materials for secondary batteries. The hottest fields are located at the top of the map and are covering the area of MXenes in general and titanium (aluminum) carbide MXenes or porous titanium carbide MXenes more specific. These fields are located at the edge of the field map, indicating that these are outliers with little connection to the other fields (yet).

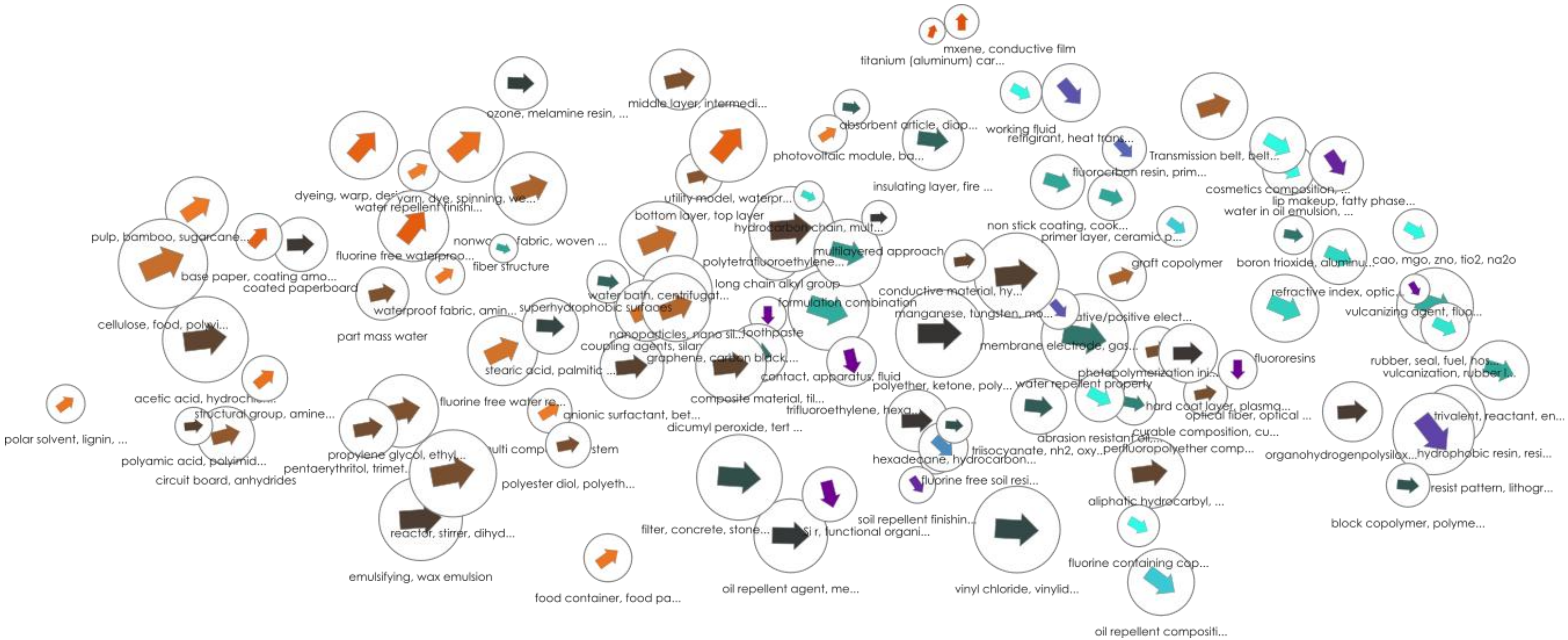

Figure 8: Mynd field map. Each coherent field of discussion that was identified in the dataset by Mynd is displayed as a circle with a size, arrow (and matching color), position and title. The size is a measure for the number of publications on this field, whereas the arrow (and matching color) indicate the recency (Orange for hot, black for mainstream, and purple for declining. X- and y- axis don't have a specific meaning, but the distance between fields is a measure for the contextual overlap they have. The closer fields are positioned, the more context they have in common.

Alternatives

An analysis of potential non-fluorinated alternative compounds for PFAS identified with Mynd can be found in figure 10. The compounds are plotted as a function of volume (number of patent families) and recency. Although the interpretation of such a plot is straight forward, it requires some initial explaining.

A general volume-recency plot can be found in figure 9 for didactic purposes. The volume recency plots have the goal to visually **quantify the forefront of innovation**. For each data point this plot indicates how much discussion (volume) there is (y-axis, log scale), and how recent this discussion is (x-axis). Such a plot always has a pyramid shape (if enough datapoints are available), which can be easily understood in terms of innovation lifecycles. The position of these concepts in the pyramid determines their position in the innovation lifecycle:

- **Dominating/established** concepts: At the top of the pyramid. A lot of publications, neither old, neither super recent, just mainstream concepts that everyone in the field should be aware of.
- **Emerging** concepts: Bottom-right. Very recently ideated, and therefore not a lot of volume yet. Further R&D activities will determine if they earn a place higher up the pyramid or not.
- **High potentials**: In between the emerging and dominating concepts. These concepts are no longer super recent, they have already gained some traction in volume, and they stay on top of mind according to recency value. Continued research thus indicates they are worth further investigation.
- **Radical** concepts: Escaped from the pyramid to the right hand side. In very few occasions you can find a concept with a very high recency value and quite a high volume simultaneously. This concept did not follow the normal innovation cycle and gained significant volume in very short amount of time: a radical innovation.
- Innovation **waste**: Everything on the left hand side of the graph (low recency values) can be considered waste. The ones that are low in volume were abandoned quite fast and never gained attention. The ones a bit higher in the pyramid did gain traction but are either well mastered and implemented by now, or they turned out to be dead end streets.

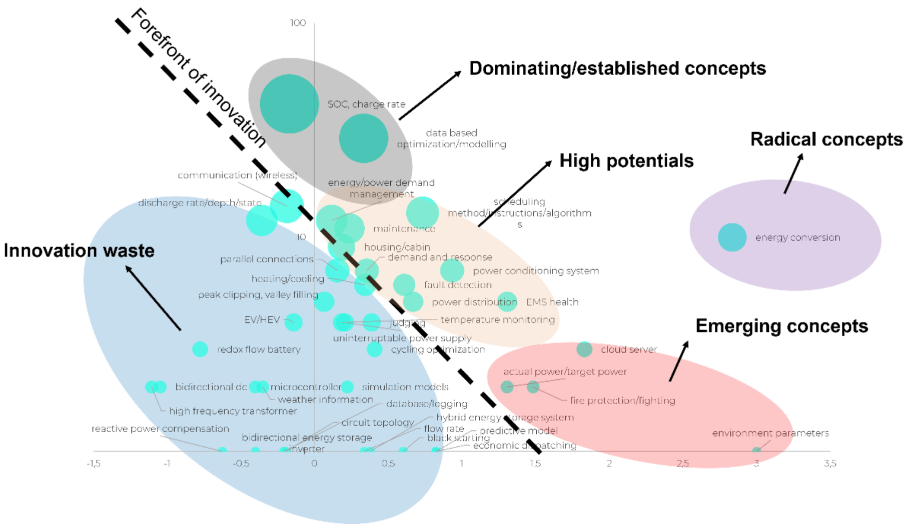

Figure 9: General volume recency plot to indicate how such an analysis should be interpreted.

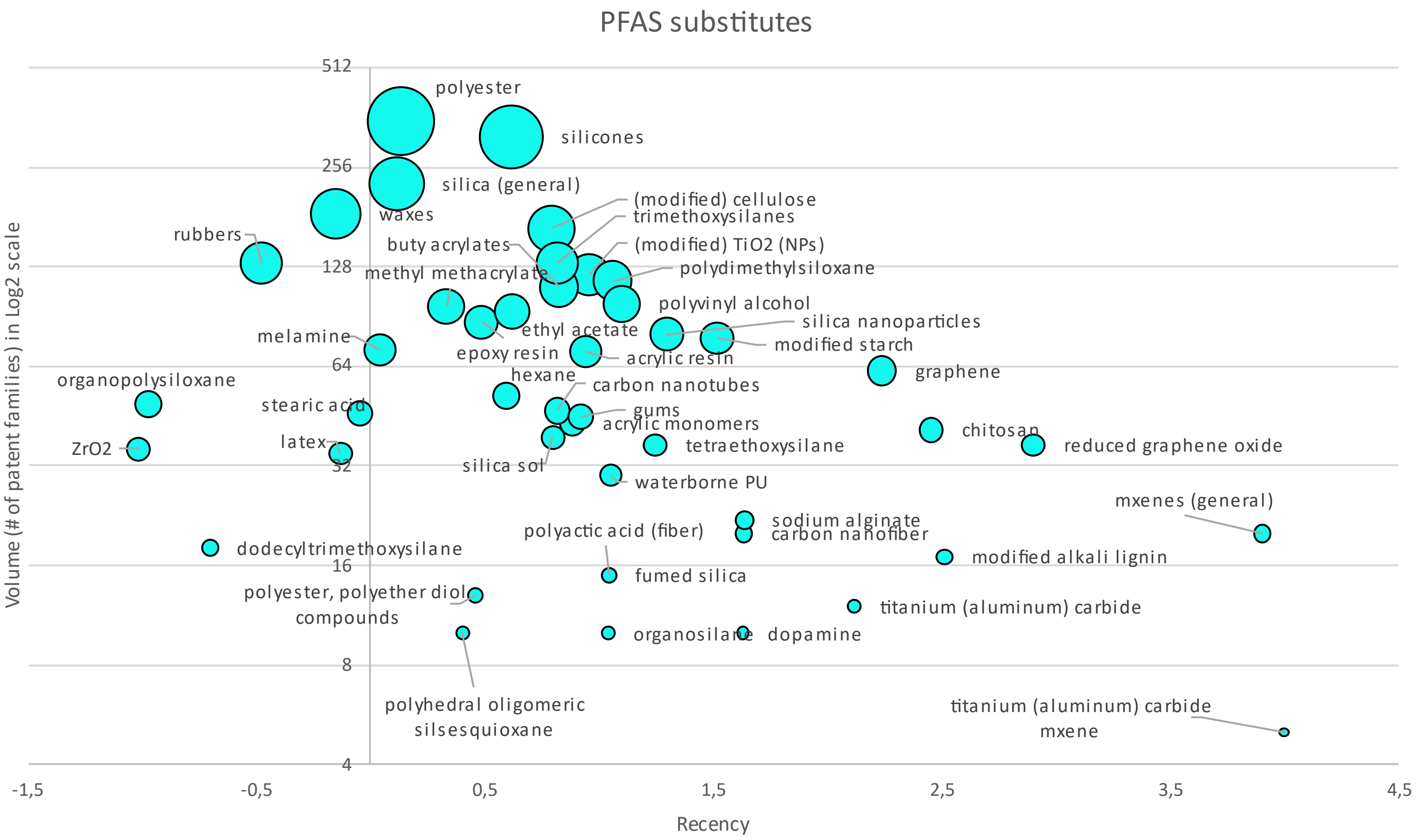

Figure 10: Volume-recency plot of PFAS substitutes. Each compound is represented as a function of volume (amount of patent families) and recency (horizontal axis). The volume (or vertical) axis is represented in a logarithmic scale (log base 2) as to enhance the readability.

From figure 10 it can be deduced that a wide variety of materials are being scrutinized to replace PFAS compounds with a non- or at least less hazardous compound.

- The dominating compounds (top) are polyesters, silica, waxes and silicones, of which silicones are considered slightly more popular.
- A large number of high-potentials are identified as well, being: (modified) cellulose, trimethoxysilanes, (modified) TiO_2 (nanoparticles), polydimethylsiloxane, polyvinyl alcohol (PVA), silica nanoparticles, modified starch and graphene.
- Another group of potentials – though slightly less hot than the ones above – are: methyl methacrylates, ethyl acetates, epoxy resins, acrylic resins, hexanes, carbon nanotubes, gums, silica sols, tetraethoxysilane, waterborne PU and acrylic monomers.
- Bottom-right, quite some emerging substitutes are identified, of which some already start to see traction in patent activity: Titanium (aluminum) carbides and MXenes thereof, MXenes in general, reduced graphene oxide, chitosan, modified alkali lignin, sodium alginates, carbon nanofibers and dopamine.

Applications

PFAS compounds are renowned for their widespread application. In this respect, the correlation between the identified substitutes and a range of applications is investigated in both figure 11 and 12. The heatmap in figure 11 maps the substitutes on the vertical axis, versus the applications on the horizontal axis. The strength of correlation between the substitutes and applications is represented by a grey scale. Black represents the largest number of patents containing a specific material-application combination, whereas white means this combination is not covered in patents. Both vertical and horizontal axis were shuffled automatically as to group similar patterns together. Hence, substitutes that are patented for very similar applications should be grouped close together, and vice versa for the applications. The axes of figure 12 are setup in the same way, but here, the color gradient represents the recency of the correlation. As such, this graph allows to focus more on recent inventive combination, rather than spotting the large and perhaps trivial correlations.

The heatmap in figure 11 shows that quite a lot of substitutes are being patented for a very wide spectrum of applications. Silicones, polyesters and rubbers are even correlated with every single application mapped in this study. Vise versa, it is clear that for most of the applications a very broad spectrum of substitutes has been looked into. Despite that, the dominant focus lies on the filters, fibers, papers and fabrics on the application side, versus the typical mainstream substitutes (i.e. silicones, polyesters, rubbers, waxes, silica). However, it is interesting to note slight nuances and different accents. Some materials (e.g. sodium alginate and modified starch) have a larger correlation with paper and packaging, whereas others (e.g. MXenes, carbides, graphene) have a closer match with the semiconductor applications. As such, it can be concluded that there's no one size fits all solution. Instead, solutions will rather come from combinations, posing a multi-facetted approach.

Figure 12 shows that the more recent combinations are drifting away from the mainstream combinations. Lithography, dielectric insulation, inks and printing are for instance receiving more recent interest – at least in combination with MXenes, carbides, graphene and reduced graphene oxides. Similarly, research on the mainstream applications is finding its way to newer materials.

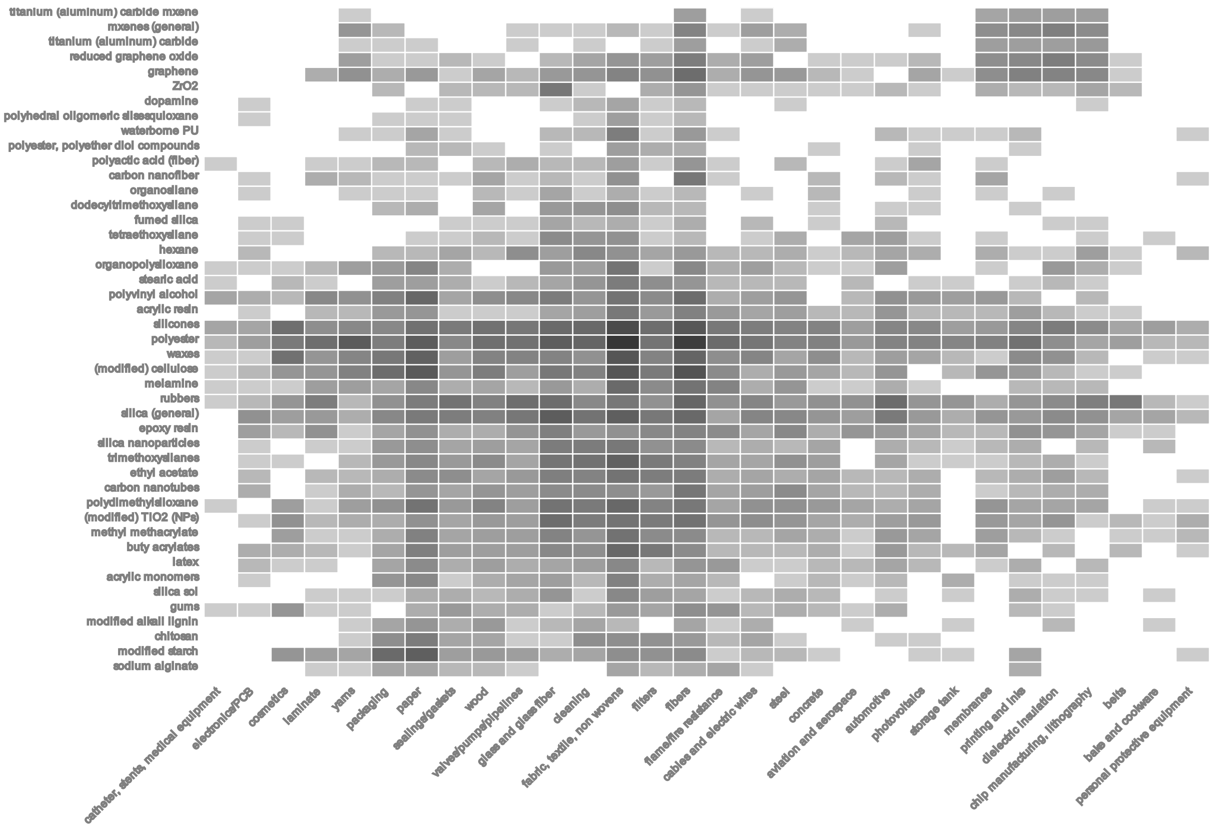

Figure 11: Heatmap visualizing the correlation between PFAS substitutes (vertical axis) and applications (horizontal axis). The grey scale is measure for how many patents mention that specific material-application combination.

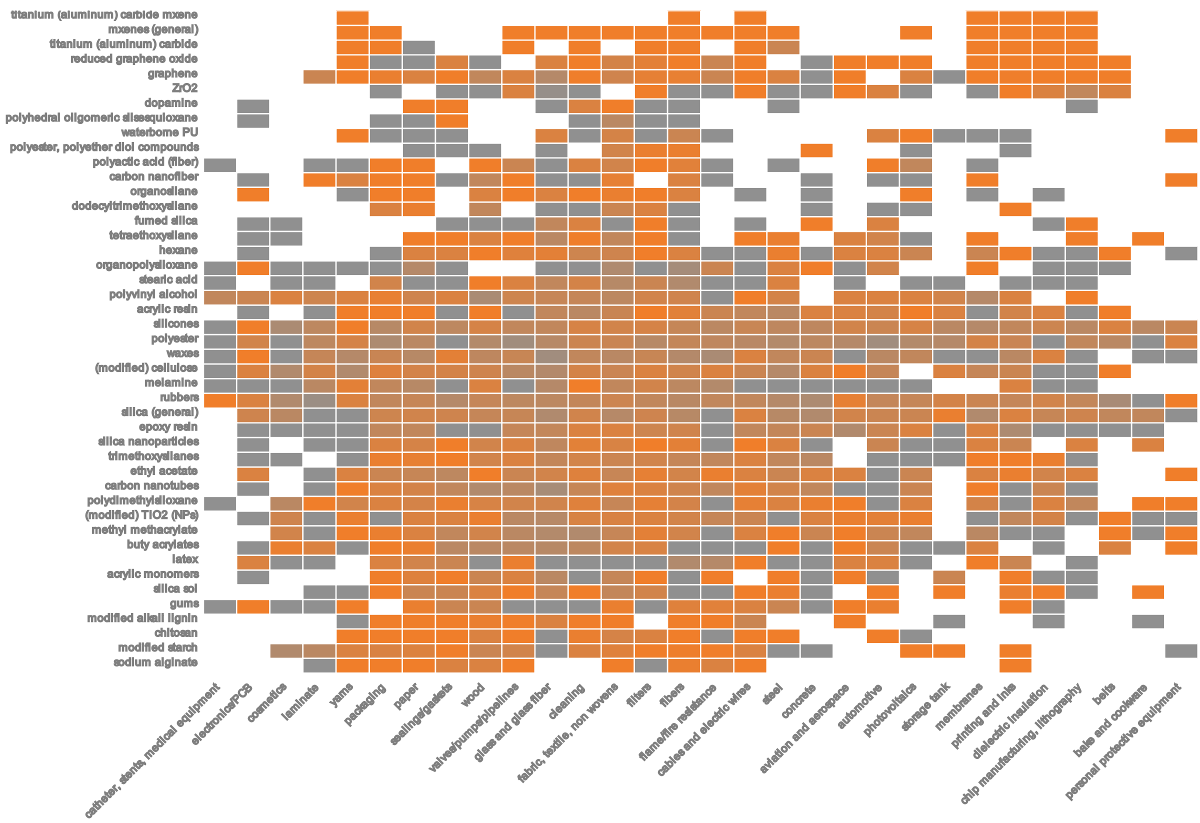

Figure 12: Heatmap visualizing the recency of the correlation between PFAS substitutes (vertical axis) and applications (horizontal axis). The recency scale goes from declining (grey) to hot (orange)PFA

6. Conclusions

In this report, we have examined innovation efforts in the global chemical industry with a focus on patent activity, international comparisons, and trends related to the substitution of poly- and perfluoroalkyl compounds (PFAS). The insights gathered present a comprehensive overview of the current state of the industry, emphasizing several key areas of significance.

Surge in patent activity

One of the most prominent findings in our analysis is the substantial increase in patent activity, particularly since 2011. Notably, the year 2020 witnessed a remarkable jump, with approximately 50% more patents filed compared to the preceding year. Although not proven, this surge in patent activity could be closely associated with the evolving regulatory landscape within the PFAS industry and the increasing public concern or awareness.

China has a growing dominance in patents

China has emerged as a dominant force in the patent realm of PFAS substitution. Not only does China possess the largest amounts of patents, its patent portfolio is expanding at a fast pace compared to other major global players. In contrast, Europe, with the exception of Germany, exhibits remarkably low patent activity, indicating room for growth and increased innovation.

Academic and corporate innovation

The company analysis shows that both upstream and downstream players are actively engaged in innovation. The analysis of the academic players on the other hand proves that the patent landscape is predominantly taken by Chinese universities. Although we did not examine publication activity in academic journals, this indicates that the engagement of European universities in PFAS substitution R&D activities has room for improvement.

Emerging trends and dominant focus on fibrous materials

Insights from the CPC classification analysis and the Mynd-generated topic model, underscore that the primary focus lies in the modification of fibrous materials, such as fabrics, filters, membranes, papers, and packaging. However, it is essential to note that certain applications, including semiconductor manufacturing, dielectric insulation, cosmetics, and soil repellants, have not seen a comparable surge in innovation. Nevertheless, the report highlights an increased innovative activity in areas such as photovoltaic modules (PV modules), secondary batteries, and transmission belts. These emerging trends indicate a shift in the industry's priorities, reflecting the dynamic nature of market demands and technology evolution.

Exploration of alternative materials

With the growing regulatory pressure and environmental concerns surrounding traditional fluorinated compounds, the industry is actively exploring alternative materials. This analysis reveals a diverse array of materials being considered as substitutes, at varying stages of technology readiness. However, we'd like to emphasize that this report did not examine whether they are truly non-hazardous or simply another replacement with toxic properties. The most established substitutes are polyester, silicones, silicas, waxes and rubbers. Modified cellulose, trimethoxysilanes, (modified) TiO_2 (nanoparticles), polydimethylsiloxane, PVA, silica nanoparticles, modified starch and graphene exhibit less patents but are showing a large amount of recent interest and growth. MXenes and titanium (aluminum) carbides are clearly quantified as emerging substitutes that still have to prove their merit.

In conclusion, the European chemical industry is at a pivotal juncture, where heightened patent activity and evolving regulations are reshaping the landscape. Despite the large focus on fibrous materials, the wide variety of applications and alternatives indicates innovation on many fronts. The surge of Chinese patent dominance however raises questions about Europe's innovation position in this global field of sustainable PFAS substitution.